MEMS Spatial Light Modulators for Real Holographic 3D Displays

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Abstract

The demand for 3D displays for virtual, augmented and mixed reality is increasing rapidly. While there are a number of such displays already available, there is still a need for improvement of the user experience. The best possible solution is the full reconstruction of a natural light field by real holography for perfectly realistic images. For this, a novel type of piston mode micro mirror spatial light modulator (SLM) is required, with pixels of only a few micrometers pitch precisely addressable to one of many deflection states. Fraunhofer IPMS and SeeReal together with consortium partners started developing such an advanced MEMS (micro electro mechanical system) SLM with unique properties.

1 Introduction

Regular and extended use of 3D displays demands a natural visual experience without physiological side effects for the user and without limitations in depth perception. The best possible concept is real holography, which produces realistic images with all natural depth cues. The term 'holography' unfortunately is widely used for all kinds of displays where the screen is not readily visible, often even for 2D imaging. In this paper we use this term in its original sense only for a display that realistically reconstructs the field of light in 3 dimensions just as if it came from a real object. A display, as opposed to a still image, moreover allows to update the image to show moving scenes.

Holographic displays thus require the spatial and temporal modulation of coherent light, see Figure 1. To keep the effort at all manageable, only a small 'viewing window' for the users eyes needs to be provided with light content, see also [1]. Even then, the SLM will have quite challenging specifications: many millions of pixels of only a few micrometers pitch, precisely addressable to one of many deflection states at frame rates of more than one kHz.

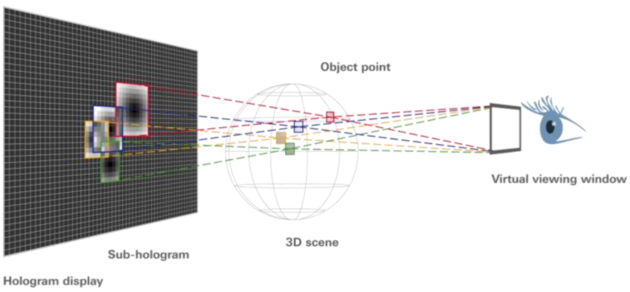

Figure 1: A piston micro mirror array can modulate coherent light to produce fully realistic 3D images.

Such modulators are not available today, but IPMS and SeeReal together with consortium partners are currently developing one within the EU H2020 project REALHOLO. The work is based on decades of IPMS experience at developing SLMs for other applications, excellent SeeReal experience at developing real holographic 3D displays, and contributions of consortium partners in various fields like CMOS backplane design and fabrication, packaging, addressing electronics, and demonstrator setup.

For a good quality holographic image, the project partners anticipate that the SLM needs to fulfil the specifications in Table 1.

parameter	value
pixel count	4000 x 2400
pixel size	4µm x 6µm
frame rate	> 1kHz
deflection range	0 … 350nm
deflection precision	8 bit
mirror tilt	< 0.1°
driving voltage	0 … 3.6V
power dissipation	< 2.5W

Table 1: key SLM specifications

All the 9.6 million MEMS mirrors need to be driven individually. For this they will be monolithically integrated on top of an fabricated CMOS backplane with a very high bandwidth data interface and integrated digital-to-analogue converters (DACs).

The limitation in driving voltage is partly due to the small pixel pitch that offers only space for small transistors that can't handle very high voltages. Another argument is the power dissipation, which increases with the square of the driving voltage.

2 Existing SLMs

Phase modulation of coherent light can be achieved by existing SLMs based on LCoS (liquid crystal on silicon) technology (e.g. [2]). Compared to these, micro mirror arrays (MMAs) can have many advantages for real holography: the phase across a pixel is more uniform, there may be much less cross talk between neighbor pixels, they can be switched much faster, and are independent of polarization.

Well-known MMAs are offered by Texas Instruments (e.g. [3]). These, however, have been optimized for 2D-image projection and are not well suited for holography: the pixels deflect in tilt mode instead of the piston mode suited for holography and there are only two possible addressing states for each pixel instead of the many required here.

The few existing piston-mode MMAs (e.g. [4] to [6]) usually have quite large pixels (several ten micrometers and more) and therefore much too few pixels for good quality holography.

3 Novel Comb Drive Actuator

The basic concepts for a novel SLM fulfilling the demands have been worked out by IPMS and SeeReal. We found that the parallel-plate actuators used in known MMAs may not be feasible for this task. To avoid the well-known pull-in, the actuator gap for these has to be quite large: for visible light about 350nm stroke and about 1,8µm of actuator gap is the minimum. This results in only very small forces and the hinges can only be quite fragile and sensitive to fabrication tolerances, as discussed in [8].

The high aspect ratio of the tightly packed actuators will also produce a severe crosstalk between neighbor pixels. As an example Figure 2 shows a 2D FEM simulation of 2 neighbor parallel-plate actuators with a 4µm pitch and 2µm actuator gap. Here the left pixel is supposed to be not deflected, while the right one is deflected to 300nm. An extraction of the electrostatic forces from the simulation shows that the force acting on the left pixel is about 4% of the force on the right one. If one included the neighbors on the other 3 sides in 3D, the cross-talk could reach up to 14%. With this, the required deflection precision (8bit) would be completely out of reach.

In principle one could try and reduce the cross-talk by reducing the electrode size and/or by introducing shielding structures between pixels within the actuator gap. This would however further reduce the already small actuator forces and it is very questionable whether the required precision could be reached at all.

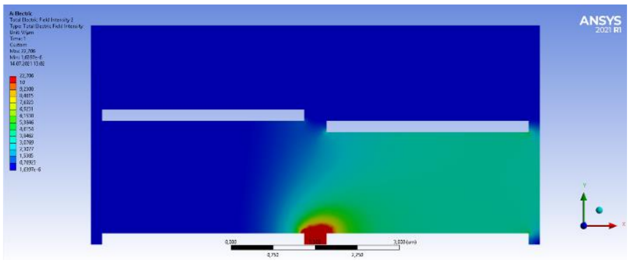

Figure 2: FEM electrical field strength simulation of two neighbor parallel-plate actuators showing strong cross-talk

In addition, the response curve of parallel plate actuators is very non-linear (see Figure 4), so that the precision of the addressing voltage has to be much better than the required precision of the deflection.

All these drawbacks can be overcome by a comb-drive actuator, see Figure 3 for a basic sketch. With a comb drive actuator, there is no pull-in in the stroke direction. Therefore, the electrodes can be much closer to each other, on the order of 200nm. Much higher actuator forces can thus be generated in spite of the reduced electrode area.

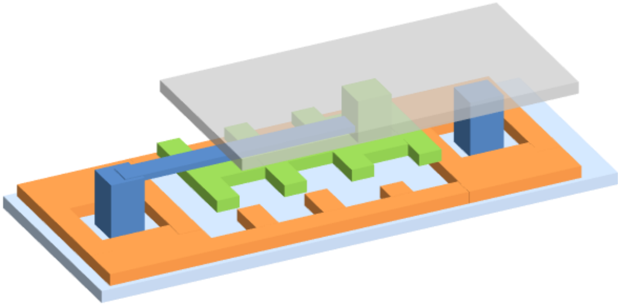

Figure 3: first concept sketch of our novel MEMS comb drive actuator for large arrays of micro mirrors at a pitch of only a few micrometers.

Figure 3 shows an asymmetric actuator with only one hinge and one fixed post. This is a very favorable design for small pixel pitch and large deflections, especially with the limited voltages and therefore actuator forces available. Properly designed the actuator can be force-balanced and may show a pure, tilt-free piston motion, see [7], patent pending.

With fabrication parameters optimized for the desired stroke, the response curve of a comb drive actuator can be quite close to linear, see Figure 4 and [8], so the precision requirement for the addressing voltage is relaxed.

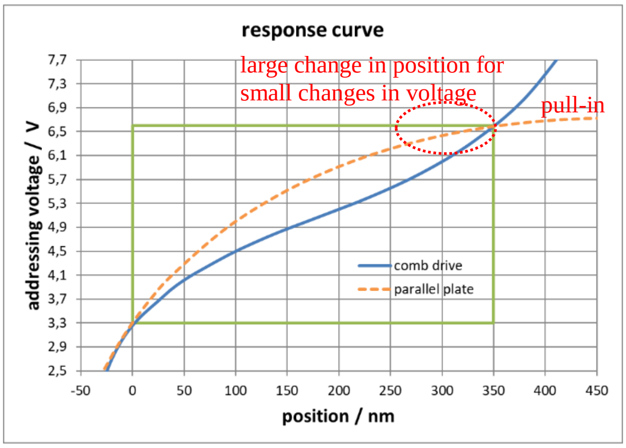

Figure 4: The response curve of a comb drive actuator (blue curve, from FEM simulations) does not get as sensitive as the one for parallel plate actuators (orange dotted curve) within a region of interest (green box) and does not end with pull-in.

With the comb drive actuator the electrical field is confined to the close vicinity of the comb fingers, see Figure 5. The exact cross-talk values depend on a number of parameters, but this way a precision even better than 8 bit can be reached.

However, the first comb drive concept of Figure 3 still has some issues. Already a small misalignment between the two combs may cause quite large torques from horizontal forces and a mismatch of the vertical forces on opposite sides, resulting in a too large mirror tilt. The comb drive is much more sensitive in this respect than the parallel plate actuator.

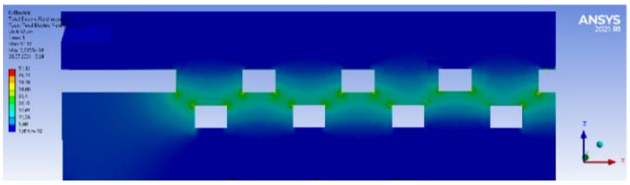

Figure 5: 2D section of 3D FEM electrical field strength simulation of a comb drive actuator showing the nice confinement of the electrical field to the close vicinity of the comb fingers resulting in low cross-talk

A second point is, one would like to have a common voltage on all the mirrors, as otherwise one gets again some cross-talk from the electrostatic field between neighbor mirror edges. As the slits between mirrors should be small for a good fill factor, this cross talk can again easily reach many percent of the stroke, which we cannot accept here. Therefore, in Figure 3 the orange comb would have to carry the individual pixel voltage and would have to be isolated and mechanically separated from the neighbor. Therefore the circumference of the comb and thereby the actuator force can only be smaller than would be possible if the outer comb would carry the common voltage.

Another concern is the isolating material below the actuator (light blue in Figure 3). From past experience we know that such isolators can trap electrical charges that influence the actuator position. Unfortunately these charges are not very stable and change quite unpredictably over time depending on the electrical fields and temperature.

Finally, we also have to consider the circuit below the actuator, which can exert an additional unwanted electrostatic force. This force can be quite large due to the substantial area of the moving comb. It will also change very non-linearly with deflection similar to a parallel-plate actuator and severely impede the deflection precision.

To solve all these issues we came up with the actuator design of Figure 6. It has two hinges in different MEMS layers acting as a parallelogram guide for the mirror. Therefore, there will be only very small unwanted mirror tilts even with some actuator torque from non-ideally aligned combs. The two hinges also can carry the two different electrical voltages needed to drive the actuator.

The lower half of the actuator is connected to the CMOS addressing circuitry below. It consists of a base plate (cyan in Figure 6), lower hinge (dark blue), and lower (moving) actuator comb (green). All these MEMS layers carry the individual pixel voltage, so there won't be any electrostatic fields between them. And there are no isolators (except for native oxide layers) that may trap electrical charges. The actuator is properly shielded from the circuit below by the base plate, and this base plate also offers a large area for the direct connection to the addressing CMOS.

The upper half of the actuator consists of the fixed comb (orange in Figure 6), the upper hinge (dark blue), and the mirror (transparent grey). This upper part is mechanically mounted on but electrically isolated from the lower actuator part and carries the common actuator voltage. The fixed comb is shared between neighbor pixels. Therefore it does not need any isolation gaps and thus can be the largest possible size for large actuator forces. The common voltage can be fed in at the array edge and no extra wires are required for this within the array.

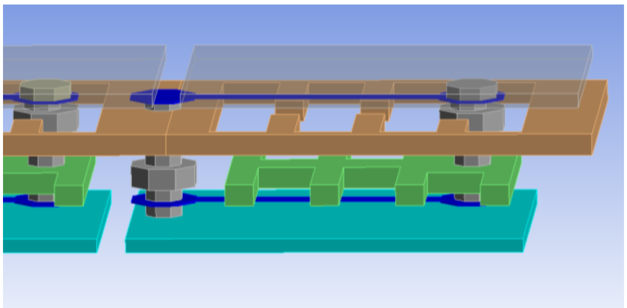

Figure 6: improved comb drive actuator with double hinge for best possible tilt-free piston movement and overall precision

Through the upper hinge all the mirrors are connected to the common voltage of the fixed comb, so no cross-talk can occur here. There are again no electrical fields and no isolators (except for native oxide layers) between these MEMS layers avoiding possible trapped charges.

In this actuator design there is also very little chance for short cuts between neighbor pixels or between moving and fixed combs due to defects in fabrication, so the overall yield should be acceptable even for large arrays.

All the advantages of this design should outweigh the more complicated MEMS process needed for the fabrication.

4 Complex Valued Light Modulation

Holographic image generation can in principle be done by modulating the phase of the incident light only, which is what piston pixels do. An observer is of course sensitive to the light intensity, not the phase. The intensity image is formed in the far light field by interference of the phase shifted light bundles.

It is quite straight-forward to calculate the far-field light field from a given map of phase shifts or pixel positions by a Fourier transform, assuming a homogeneous (or otherwise known) illumination of the SLM. However, in case of computer-generated holography the task is to solve a more complicated problem. Here one needs to compute the phase map on the SLM from the desired intensity distribution in the observation space under the constraint of the given SLM illumination intensity distribution.

The state-of-the-art approach of phase-only holographic encoding is using iterative algorithms like Gerchberg-Saxton ([9],[10]), which are power- and time consuming. For real-time displays, this is a drawback.

Alternatively, the encoding of complex holograms requires much less effort. Here one modulates the incident light both in phase and amplitude, which requires some additional optical elements but simplifies calculations such that they can be done in real-time with much smaller effort.

For larger LCD pixels the generation of complex holograms is well established for real-time encoding at SeeReal by combining the light from two neighbor phase pixels on the base of a birefringent crystal and a structured retarder, see [11].

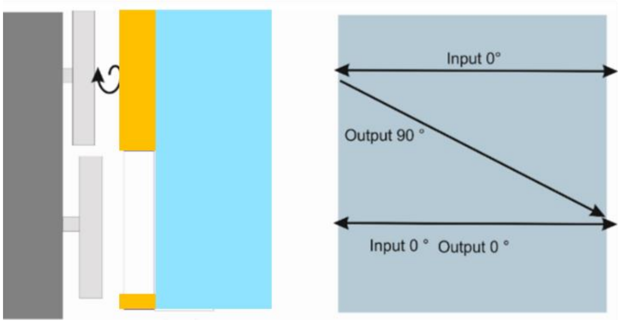

Figure 7: optical principle of complex light modulation by two neighbor phase shifting pixels

The beam combiner works like this: the incident light in Figure 7 (from the right) is polarized as the ordinary ray of the birefringent crystal (grey) and so passes it straightly. For the lower pixel the light continues unchanged to the MEMS mirror and comes back with the desired phase along the same trajectory.

For the upper pixel, however, the polarization is changed by the retarder (orange on the blue glass carrier) on the first pass to circular polarization. The phase is adjusted independently of the lower pixel by the position of the upper mirror. The reflected light polarization is changed back to linear by the retarder on the second pass. Now, however, it is the extraordinary ray, which is broken on normal incidence by the birefringent crystal. The thickness of this crystal is chosen so that this ray exits just in the same spot as the ray from the lower pixel. On exit, the extraordinary ray is again broken so that it is also leaving in the same direction as the lower pixel ray.

Finally, a linear polarizer (not shown) at 45° to both polarization planes mixes the two beams so that they can interfere with each other, resulting in a beam with the desired phase and amplitude.

With the beam combiner the SLM of course loses its advantage of being polarization independent, but in some cases the advantages of complex modulation are more important. For other cases the SLM can be used in a phase-only variant without the beam combiner.

The retarder has to be positioned relative to the pixel matrix with high precision in one lateral dimension so that one of a pair of neighbor pixels is fully covered by the retarder layer, while the other one is fully free. The retarder also has to be in close proximity to the pixels.

Given the small pixel pitch and rather large SLM area, the retarder mounting and alignment is not at all trivial. It has to be stable for a quite large operating temperature range. Therefore, the thermal expansion coefficient of the carrier glass of the retarder has to be matched quite well to the MEMS chip.

The birefringent crystal (grey in Figure 7) needs to be cut in the correct orientation, but its positioning doesn't require too much accuracy.

5 Summary

The MMA-based SLM developed by Fraunhofer IPMS, SeeReal, and partners will exhibit optical properties far superior to all existing alternatives. The improved quality of the modulated light will allow a high-quality holographic image generation.

6 Acknowledgements

The project REALHOLO has received funding from the European Union’s Horizon 2020 research and innovation program under grant agreement No. 101014977. It is an initiative of the Photonics Public Private Partnership. The REALHOLO project consortium includes 6 further partners from 5 different European countries. Together we will set up a complete demonstrator 3D head-up display system.

See also: https://realholo.eu/

7 Literature

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